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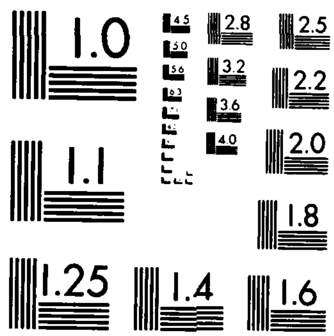

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ULTRASONIC OXYGEN SENSOR

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Applied Technologies, Inc.
6395 Gunpark Drive, Unit E
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December 1987

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Approved for public release; distribution is unlimited.

Prepared for
USAF SCHOOL OF AEROSPACE MEDICINE
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Brooks Air Force Base, TX 78235-5301

Volenti Subvenimus

NOTICES

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This report has been reviewed and is approved for publication.

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The respirable gases generated by an on board oxygen generation system (OBOGS) are comprised of a mixture of oxygen, argon, and nitrogen. This gas mixture can be measured ultrasonically to determine the concentration of oxygen within the mixture. This final report describes an ultrasonic measurement system that has been successfully tested to a simulated altitude of 20,000 ft. The concentration of oxygen calculated from ultrasonic data is accurate to approximately 1% over the range of 21 to 95%. In addition to measuring the concentration of oxygen, the ultrasonic oxygen sensor can also measure the flow rate of the respirable gases produced by an OBOGS accurate to approximately 1.6 L/min.

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ULTRASONIC OXYGEN SENSOR

INTRODUCTION

The U.S. Air Force School of Aerospace Medicine (USAFSAM) awarded Applied Technologies, Inc. a Phase II Small Business Innovation Research (SBIR) program contract to develop a prototype ultrasonic oxygen sensor. The contract was awarded in response to a proposal submitted in December 1986 to design and develop an oxygen sensor which could measure the oxygen (O_2) concentration and flow rate of respirable gases of a USAF on board oxygen generation system (OBOGS).

The results of a Phase I study established the feasibility of using ultrasonics to measure the speed of sound (C) of a breathing gas consisting of oxygen, argon, and nitrogen. At low flow rates OBOGS produced oxygen and argon at a nearly constant ratio, but at higher flow rates, its output also included nitrogen. The oxygen sensor was designed to measure O_2 concentration from a low value of 21% to a maximum value of approximately 95%.

By *determining* C *for* a variety of gas mixtures, it was possible to derive a quantity, a gamma/molecular weight (γ/M), for any concentration of the gas mixture. This value, plotted against a measured value of O_2 concentration, produced a curve, that for any C measurement of a gas mixture, an O_2 concentration could be derived.

By using data gathered on the ultrasonic time of flight, a value of velocity (V) can also be calculated for the gas flow. With the cross-sectional diameter of the ultrasonic chamber gas passage channel in the program, the microcomputer can calculate the gas flow rate in ambient liters per minute.

The ultrasonic oxygen sensor was operationally tested at Brooks AFB, where the sensor was installed in an altitude chamber; it was attached to an OBOGS through a mass flowmeter. The O_2 concentration of the OBOGS was monitored by a Perkin-Elmer Medical Gas Analyzer. The sensor was subjected to simulated altitudes to 20,000 ft at flow rates to 50 standard liters per minute.

SYSTEM DESCRIPTION

The basic system used to measure O_2 concentration consisted of an ultrasonic chamber, a microcomputer-based control, and readout electronics. Gas temperature was measured by a calibrated thermistor probe.

The overall system configuration is shown in the system block diagram (Fig. 1).

Ultrasonic Measurement Chamber

The cylindrical ultrasonic measurement chamber was 2.7 in. (6.86 cm) in diameter and 9.7 in. (24.6 cm) in length. A cross-sectional view of the ultrasonic chamber is shown in Figure 2. A 0.75-in. (1.90 cm) diameter hole was drilled through the length of the cylinder for gas passage; it was tapped on both ends to receive a 0.75-in. (1.90 cm) male pipe adapter. A 0.5-in. (1.27 cm) hole was drilled and tapped through the cylinder at a 12-degree angle to the longitudinal axis of the cylinder. The ultrasonic transducers were mounted in stems screwed into these tapped holes. A 0.375-in. (0.95 cm) hole was drilled and tapped perpendicular to the cylinder's longitudinal axis for thermistor probe installation.

The chamber was constructed of Celcon*, an acetal copolymer which has the properties determined to be the best for fabricating and machining. The material has high chemical resistance to weak acids, bases, and hydrocarbons and has no adverse effects with the use of oxygen. The coefficient of linear thermal expansion is approximately 4.7×10^{-5} in./in./°F.

To calculate V, the ultrasonic transmissions had to be in line with the flow, or at a small angle to the flow. A single set of transmitter and receiver transducers were used and switched back and forth to obtain forward and reverse transmissions of ultrasonic energy. The forward and reverse transmissions made it possible to calculate V.

Electronics

The electronic circuits required for driving voltages, sonic pulse detection, analog to digital conversion, overall controlling, and C computation are shown in the electronics system block diagram (Fig. 3).

*Celcon is a registered trademark of the Celanese Corporation.

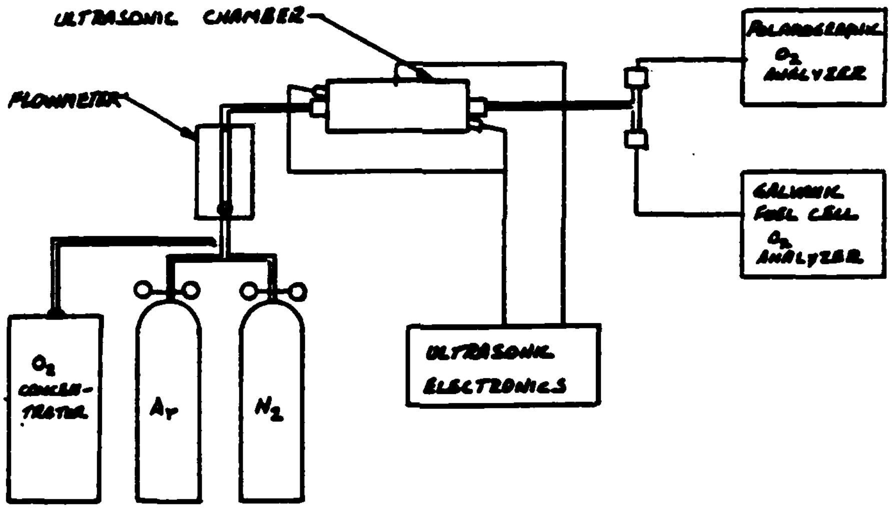

Figure 1. Measurement system block diagram.

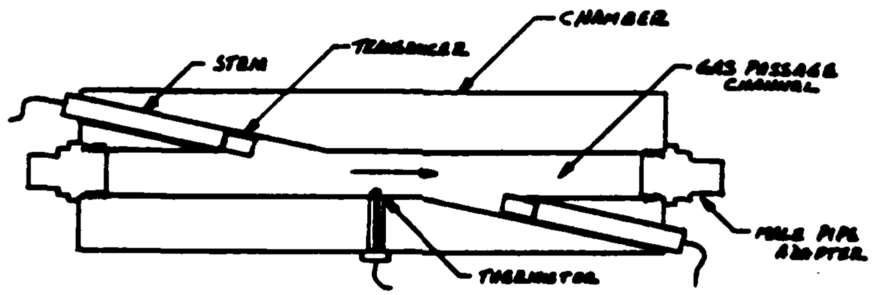

Figure 2. Cross-sectional view of ultrasonic chamber.

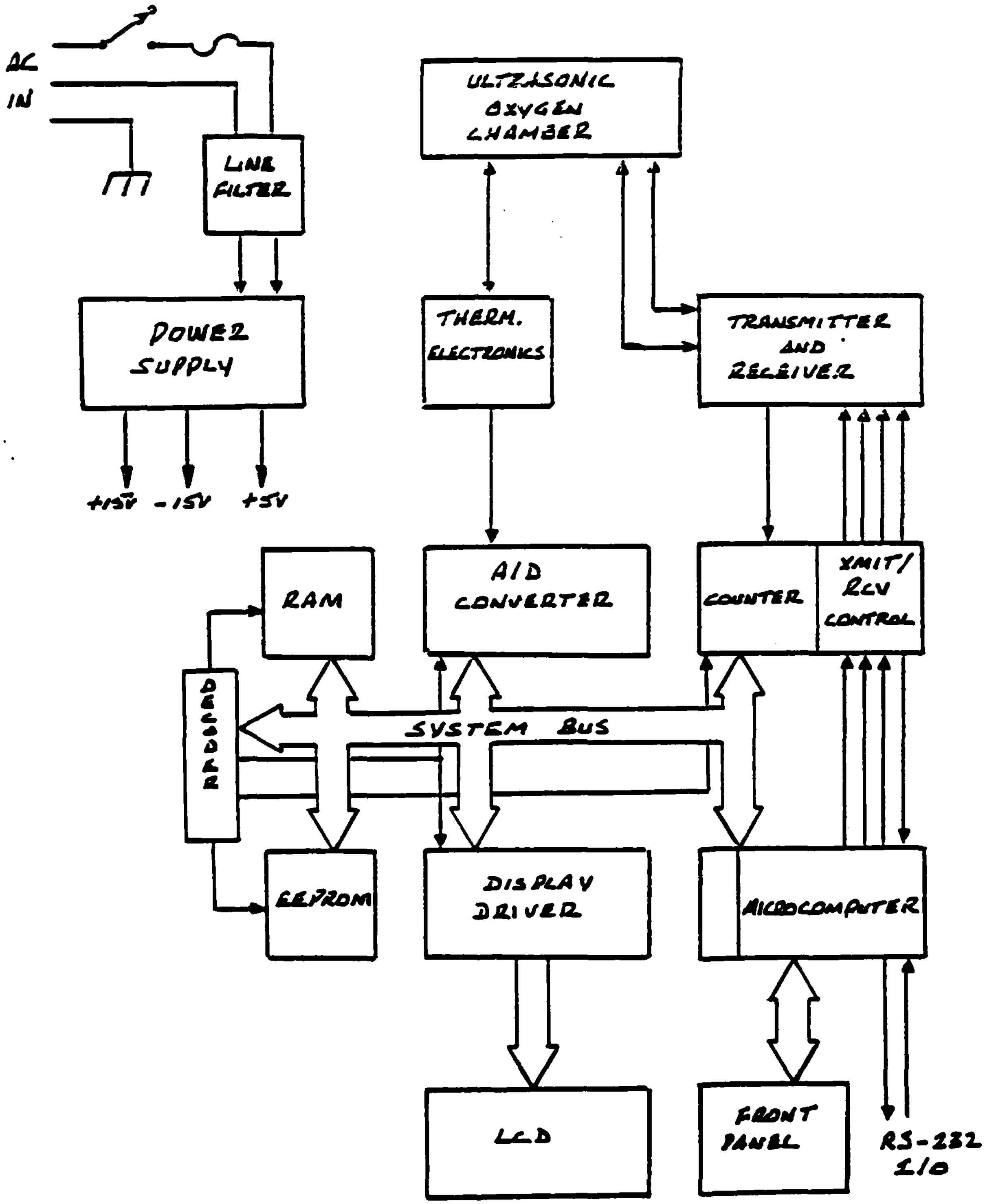

Figure 3. Electronics system block diagram.

The basic functions provided by the electronics system are as follows:

- o Generate sonic transmitter pulses.
- o Receive and detect sonic pulses.
- o Regulate the timing and summation sequence of the transmissions.
- o Convert the temperature probe from analog to digital readout.
- o Compute C, γ/M, V, and O_2 concentration.
- o Provide data output in a display mode (%O_2) and digital output to CRT or printer.

A portable carrying case contains the measurement electronic circuits. Inside the case the front panel is hinged for access to the printed circuit assemblies mounted in a card cage. Interconnections between the printed circuit assemblies are made through a motherboard at the base of the card cage.

The electronics assembly consists of the following printed circuit cards:

- o Power supply card
- o Microcomputer card
- o Transmitter/receiver card
- o Counter card
- o Analog/digital converter card

The electronic circuits for the thermistor are located in a small, shielded aluminum box attached to the side of the card cage. The enclosure shields the highly sensitive circuits against noise. Adjustment to the thermistor is made possible by small access holes in the top of the aluminum box.

On the front panel of the ultrasonic module was mounted specific switches and a liquid crystal display (LCD) for values calculated by the microcomputer.

The front panel switches and their functions are:

- o Power switch - controls the power to the ultrasonic module
- o Test switch - controls electronic setup and observation of signals
- o Master reset switch - resets the microcomputer program operation
- o Thumbwheel switch - controls the LCD display mode
- o Calibrate switch - calibrates the oxygen sensor

The LCD's indicate:

- o Concentration of oxygen (%)
- o Flow rate (L/min)
- o Temperature of gas (°C)

THEORY OF OPERATION

The theory of measuring the O_2 concentration of respirable gases is based on the computation of C for the gas being measured. The C for any gas depends on gamma (ratio of heat capacities c_p and c_v), the absolute temperature of the gas (T), and the molecular weight (M) of the gas as shown by the following equation:

$$C = \left[\frac{\gamma RT}{M}\right]^{\frac{1}{2}} \tag{1}$$

Where γ is the ratio of c_p (heat capacity at constant pressure) and c_v (heat capacity at constant volume), R is the universal gas constant (8.31434 Joules/K Mole), and M is the molecular weight.

The γ and M for each gas or gas mixture is unique and measurably different from other gases. From equation (1), the measurable quantities are C and T.

Calculations for C in the ultrasonic measurement chamber are based on the following equation:

$$C = \frac{d}{2}\left[\frac{1}{t_1} + \frac{1}{t_2}\right](n)(12)(10^6) \tag{2}$$

Where d (in meters) is the distance between the transmitter and receiver transducers, t_1 is the forward transmission time, t_2 is the reverse transmission time, and n the number of summed transmissions.

The basic measurement is made by exciting a piezoelectric crystal with a voltage sufficient to produce an ultrasonic pulse capable of propagating between the transmitter and receiver transducers. A 12 MHz clock counts from the time the transmitter pulse is initiated until the transmitted signal reaches the receiver transducer. This count (t_1) is stored and the sequence is repeated 20 times; the resulting count is added to the preceding count. A typical data count, summed 20 times, may be in the order of 80,000 counts.

The function of the transducers is then reversed and the transmitter/receiver combination is sequenced identical to the first transmission to provide a transmission count in the opposite direction (t_2). This procedure provides:

- o Data to compute speed of sound
- o Data to compute velocity

Since the distance between the two ultrasonic transducers is the same, and since there is no movement of the breathing gas within the chamber, the counts should be identical. Some discrepancies, up to 20 total counts, were noted due to the inability to precisely adjust the transducers, thus introducing minute differences in the measurements.

Concentration of Oxygen

From the data collected with the ultrasonic chamber, equation (2) can be solved for C. C can then be used in equation (1) and the equation solved for γ/M. This quantity, γ/M, is used because in actual practice neither γ nor M for the OBOGS breathing gas can be predicted.

Values for γ/M can be computed for each gas mixture at a specific temperature. These values can be plotted as a function of the O_2 concentration.

As V increases from zero, the values of t_1 and t_2 will change, one increasing and the other decreasing. The calculation of C is independent of the gas medium or its temperature.

Oxygen Flow Rate

From the same values of t_1 and t_2, V can be calculated using the following equation:

$$V = \frac{d}{2}\left[\frac{1}{t_1} - \frac{1}{t_2}\right](n)(12)(10^6) \qquad (3)$$

The distance remains the same, and the t_1 and t_2 values are the same values used to compute C. The number of transmissions that have been summed is 20. The solution of equation (3) provides V in m/s.

The cross-section of the ultrasonic chamber is known (0.75 in.). V times the cross-sectional area in the appropriate units provides the flow rate of the gas in ambient liters per minute at the axis of the ultrasonic transmission. The angle of the ultrasonic axis to that of the gas flow is 12 degrees. The flow rate at the ultrasonic axis divided by the cosine of 12 degrees provides the flow rate at the axis of gas flow, as shown in the following equation:

$$\text{Flow rate (L/min)} = \frac{V}{\cos(12)}\left[\frac{0.75}{2}\right]^2 \frac{(\pi)(2.54)(60)}{(1000)} \qquad (4)$$

$$\text{Flow rate (L/min)} = \frac{17.101V}{0.9781}$$

MEASUREMENT PROCEDURE

The procedure used to measure the O_2 concentration was done in two steps: first, the ultrasonic measurement chamber was calibrated; and second, a variety of gas mixtures of oxygen/argon and nitrogen was measured. A single bottle of prepared calibration gas was used to verify the calibration and calculated results. The calibration gas was composed of oxygen (50%), argon (2.5%), and nitrogen (47.5%).

A commercial molecular sieve oxygen concentrator was used to provide oxygen/argon gas at a low flow rate, and nitrogen was mixed with the output. The O_2 concentration was measured by two different oxygen analyzers connected in parallel. One oxygen analyzer used a galvanic fuel cell and the other, polarographic detection techniques. Both analyzers were frequently calibrated using ultra-high purity (UHP) oxygen. The drift characteristics of each analyzer were different; therefore, both were calibrated for each set of gas mixtures used, before and after each data measurement.

Thermistor Calibration

The C of a gas critically depends upon the gas temperature. A fast-response thermistor bead, Omega model 44018 composite linear thermistor probe, was used to measure the temperature. The thermistor was set to measure from -2 °C to 38 °C. The two electronic set points were -0.3417 and 1.4339 volts. These set points provided a linear deviation of ±0.03 °C.

The thermistor leads were coated with epoxy to provide a waterproof coating over the leads. The thermistor was physically bound to the quartz crystal thermometer probe so that both of the sensors would be exposed to the same water temperature. The thermistor was calibrated using water temperatures in both increasing and decreasing order.

These data were plotted as a delta from the quartz crystal temperature. The water temperature was also monitored by a bomb-calorimeter thermometer. A plot of the thermistor deviation was used to determine the maximum deviation from zero. From these data, the maximum deviation was less than 0.02 °C. It was determined that no correction to the temperature reading was required over the temperature range (15 - 30 °C). The thermistor temperature curve is included in Figure 4.

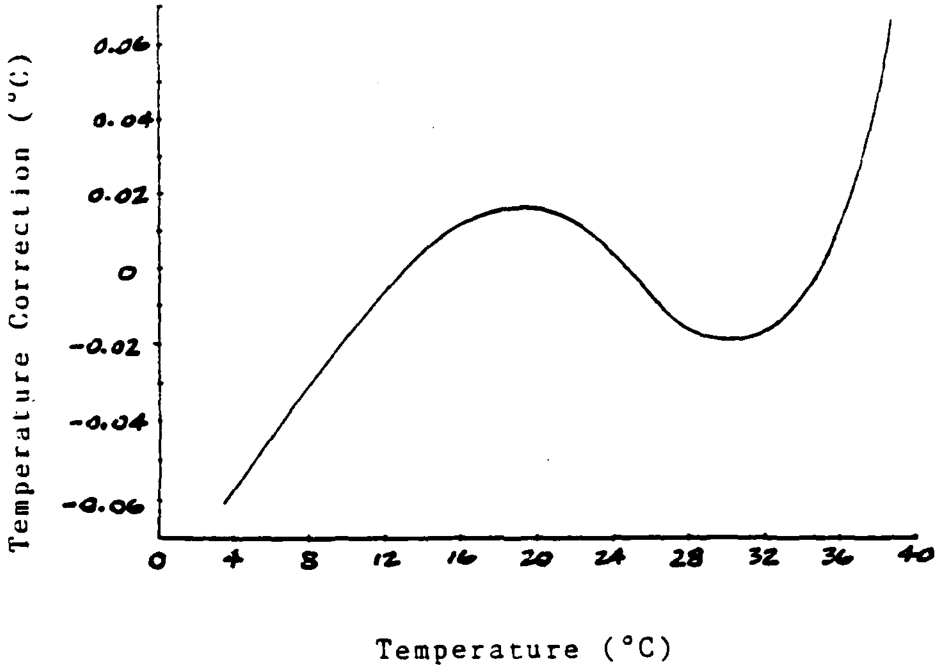

Figure 4. Thermistor probe temperature calibration.

Ultrasonic Chamber Calibration

The ultrasonic chamber had to be calibrated in order to calculate the physical distance between the two transducers. Argon and nitrogen were selected as calibration gases for two reasons: one, the gamma characteristics of both gases were well known over temperature; and two, the C for these two gases bounded the oxygen/argon and nitrogen C. Data on these gases were available from the Thermodynamics Laboratory of the National Bureau of Standards (NBS), Boulder, Colorado. NBS was especially helpful in providing data on these gases at an atmospheric pressure of 630 mm Hg. The ultrasonic chamber was calibrated at an altitude of 630 mm Hg rather than at 1 atmosphere (760 mm Hg). NBS data on argon and nitrogen are included in the Appendix.

From the NBS data on argon, a value for γ was used to compute C from equation (1). The molecular weight of argon is 39.948. The temperature at the time of measurement was noted. From equation (1) C was computed for the specific temperature of the gas measured by the thermistor. The computed C value and the value of the two transit times, t_1 and t_2, were inserted into the following equation and solved for d, in meters:

$$d = \frac{2C}{\left(\frac{1}{t_1} + \frac{1}{t_2}\right)(n)(12)(10^6)} \qquad (5)$$

Several calculations of d, using differing argon flow rates, were made and logged. Each of the calculated distances was noted for consistency.

Nitrogen was then substituted for argon and the ultrasonic chamber purged. Controlled flow rates of nitrogen were introduced into the ultrasonic chamber. Calculations, using nitrogen, were obtained for the distance, again noting consistency of values.

Electronic Delay

Theoretically, both of the calculated distances using argon and nitrogen should have been identical. It was determined that the discrepancy noted between the two gas measurements could be attributed to a constant electronic delay.

The transit count is initiated by the microcomputer and is terminated when the ultrasonic signal is detected by the receiving transducer. Several factors comprise an electronic delay in the generation and reception of the ultrasonic signal.

The mechanical inertia of the transducer must be overcome before an ultrasonic pulse can be generated. The receiving transducer must also be excited before it can generate an electrical signal, and the received signal propagates through the circuits before detection. These factors cause a delay in the order of 20 μs. This delay factor introduces error into distances calculated for argon and nitrogen.

The electronic delay (E_d) was computed using the apparent distances calculated for the two gases and the C for each of the two gases by the following:

$$E_d = \frac{d_{N_2} - d_{Ar}}{C_{N_2} - C_{Ar}} \tag{6}$$

The solution of equation (6) provided an E_d value that is subtracted from each of the t_1 and t_2 readings. From these corrected data, the distances were again calculated for each of the two gases. The results were nearly the same and an average of the distances was used in all subsequent calculations for V and C.

Oxygen Measurement

Several gas samples were used to test the measurement system for O_2 concentration. Using the calibrated O_2 analyzers, it was determined that the commercial O_2 concentrator could generate 93 - 94% oxygen. By adding minute quantities of nitrogen and measuring these mixtures with the ultrasonic O_2 sensor, a set of data could be derived for γ/M as a function of the O_2 concentration.

These data are plotted graphically in Figure 5. The graphic plot appears to be slightly nonlinear; however, the nonlinearity seems insignificant in view of the fact that a linear equation caused no appreciable error. Nonlinearity was anticipated because γ is a nonlinear function. The following equation was derived for γ/M as a function of O_2 concentration.

$$\text{Concentration of } O_2\ (\%) = \gamma/M\ (-14.5)(10^3) + 724 \qquad (7)$$

This equation was programmed into the software of the microcomputer; for each calculation of γ/M, a corresponding value of O_2 concentration was computed and displayed.

Flow Rate Measurement

A test setup was established, using a flowmeter calibrated for oxygen (±1%), to verify the flow rate measured by the ultrasonic chamber.

Using equation (3) to compute V, dividing by the cosine of 12 degrees and multiplying this value by the cross-sectional area, provided a value for flow rate that was below that measured by the calibrated flowmeter.

Using a CRT terminal to access constants stored in the electronics, the value for cross-sectional area was changed to a value that made the ultrasonic chamber flow rate agree with the flow rate through the calibrated flowmeter. As stated earlier, the cross-sectional diameter of the gas passage channel was 0.75 in. (1.90 cm); however, the transducers actually protruded into this diameter a small amount. This factor plus the male pipe adapter's inner diameter of 0.5 in. (1.27 cm) may have caused flow disturbances that influenced the flow rate theoretical calculations.

Several flow rates were measured by the ultrasonic chamber and the data observed. These data are presented in Table 1. The minimum measureable flow rate was 1.6 L/min and the maximum flow rate was approximately 65 L/min. The ultrasonic chamber could handle more than 65 L/min; however, the maximum reading on the calibrated flowmeter was 65 L/min.

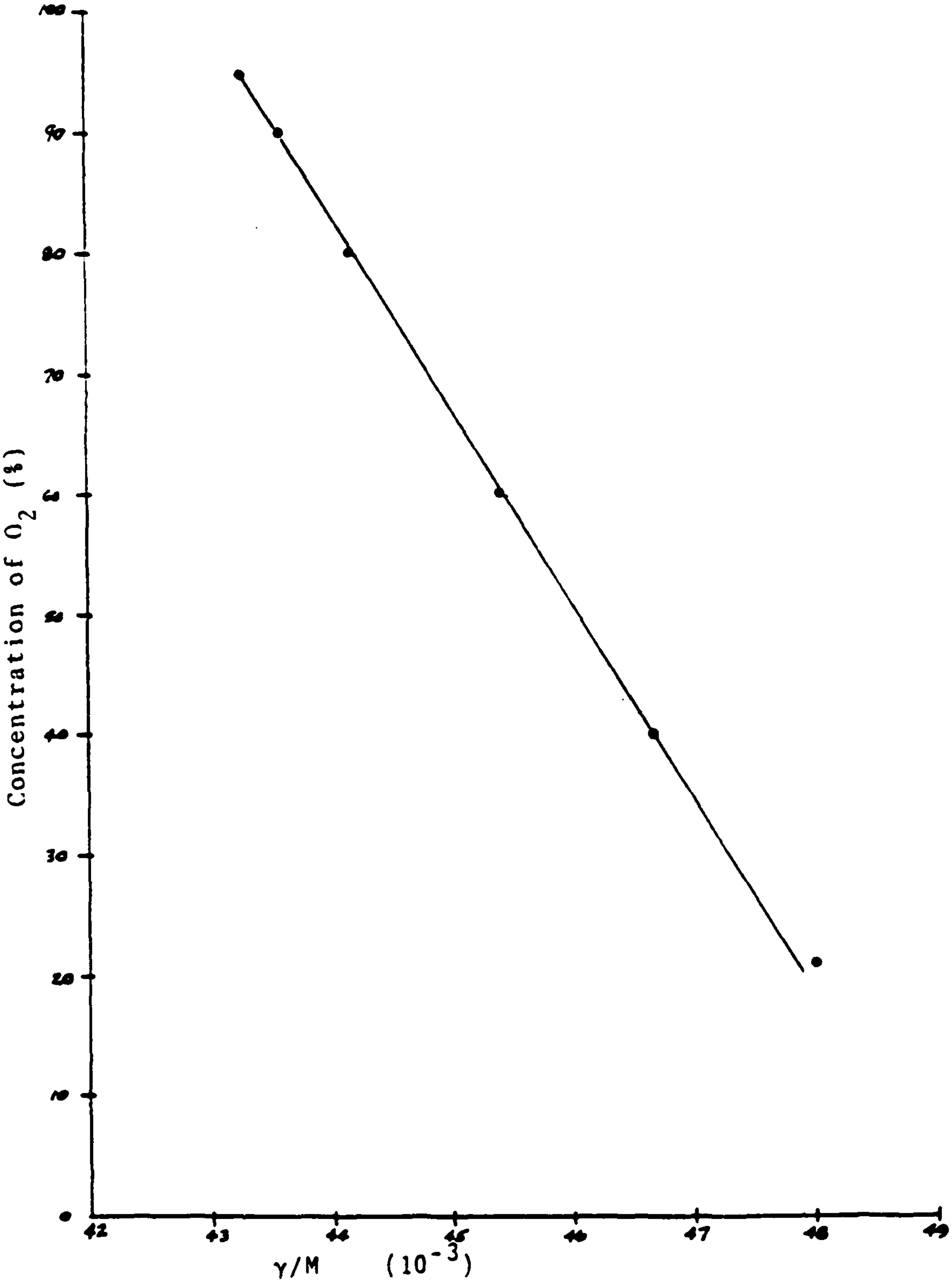

Figure 5. γ/M as a function of oxygen concentration.

TABLE 1. ULTRASONIC OXYGEN FLOWMETER DATA

Flowmeter Setting	Flowmeter (L/min)	Sonic Flow (L/min)	Delta
10	3.560	3.8	-0.240
20	7.468	9.0	-1.532
30	11.393	13.5	-2.107
40	15.387	17.1	-1.713
50	19.502	20.6	-1.098
60	23.946	24.5	-0.554
70	28.355	28.5	-0.145
80	32.833	32.5	0.333
90	37.294	37.3	-0.006
100	41.641	41.2	0.441
110	48.180	45.6	2.580
120	50.750	50.7	0.050
130	56.000	55.8	0.200
140	60.351	60.3	0.051
150	64.401	64.2	0.201

SOFTWARE

Software was generated to accomplish the controlling functions and the computations required as part of the overall design of the ultrasonic oxygen sensor system. The software accomplishes the following functions:

- o Timing and controlling input/output lines
- o Timing and controlling transmitter/receiver signals
- o Mathematical computations
- o Formatting output data
- o Displaying output data

The software was written in assembly language to reduce storage and execution times. The operating program was stored in non-volatile ROM, except that certain system functions were stored in EEPROM for protection in the event of power failures. Access to these functions allowed updates or changes to be made. These functions included the following:

- o Storage of calculated distance (d)
- o Storage of the transmission summation number
- o Transmission interval timing selection

A built-in-test (BIT) was incorporated into the software development. The internal test switch prompts the microcomputer to execute a check sum on the ROM and read the EEPROM and present a numerical number corresponding to the test results. The result is part of the digital output and can only be displayed on a CRT terminal.

Other diagnostic test functions were incorporated into the software development for troubleshooting the operation of the ultrasonic oxygen sensor through a CRT terminal. Some of the diagnostic functions incorporated were:

- o Examination of memory
- o Provision to make corrections to EEPROM system parameters
- o Examination of outputs for critical calculations in calibration and normal run-time routines

ALTITUDE CHAMBER TEST

The ultrasonic oxygen sensor was delivered to Brooks AFB to demonstrate its ability to operate at simulated altitudes up to 20,000 ft. The test objective was to determine the capability of measuring respirable gases supplied to pilots at simulated cockpit altitudes.

Altitude Chamber Test Setup

For the altitude chamber test, the oxygen sensor was attached to the OBOGS output which was measured by a mass flowmeter. The O_2 concentration of the OBOGS was monitored by a Perkin-Elmer, Model 1100, Medical Gas Analyzer. The test setup is shown in Figure 6.

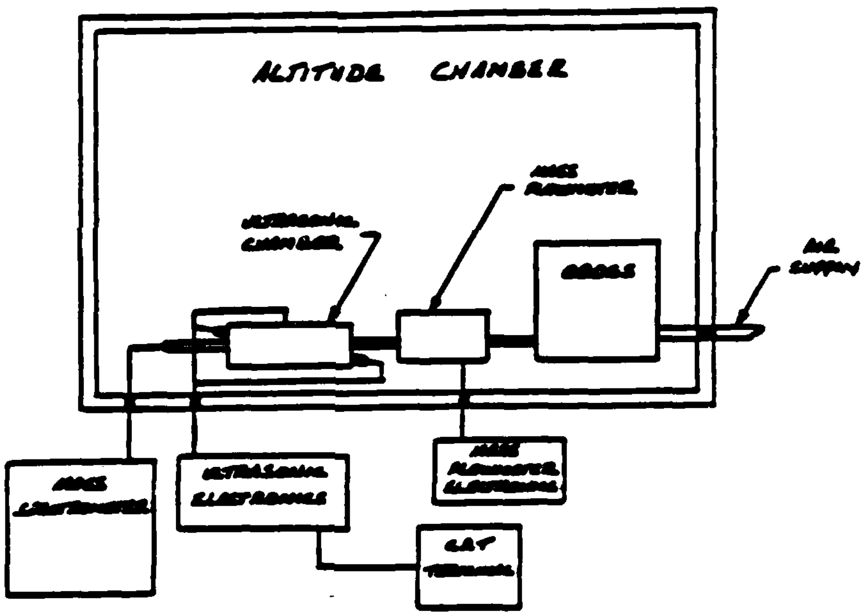

Figure 6. Altitude chamber test setup.

Cabling

A single cable connects the electronic assembly to the ultrasonic chamber. The cable was split at one end into two cable connectors, one for the ultrasonic circuits and one for the thermistor circuits. An interface connector provided for connection through the altitude chamber wall. Bayonet connectors were used to simplify electrical hookup.

Altitude Chamber Test

The altitude chamber test was conducted at different altitudes with mass flowmeter settings of 10, 25, and 50 standard L/min. The simulated altitudes were:

- Ground level (Brooks AFB elevation 749 mm Hg)
- 5,000 ft (632 mm Hg)
- 10,000 ft (522 mm Hg)
- 15,000 ft (429 mm Hg)
- 20,000 ft (350 mm Hg)

The altitude test was conducted from ground level to 20,000 ft and back to ground elevation. The comparative data were observed, recorded, and tabulated (Table 2).

At the test conclusion, the altitude was increased to a value where the ultrasonic signal became marginal. This value was 22,500 ft at a mass flow rate of 10 standard L/min.

TABLE 2. ALTITUDE CHAMBER COMPARATIVE TEST DATA

Altitude (ft)	Mass flowmeter (standard L/min)	Ultrasonic sensor O_2(%)	Ultrasonic sensor (ambient L/min)	Temperature (°C)	Ultrasonic sensor (standard L/min)	Perkin-Elmer O_2 (%)
Ground	5.0	93.9	5.3	21.8	5.7	94.2
	10.0	92.9	9.9	21.8	10.5	93.8
	20.0	81.2-82.6	19.3-20.4	21.8	20.6-21.7	81.2-83.0
	30.0	64.9-68.4	29.0-30.0	21.8	30.9-32.0	64.0-67.6
	40.0	54.5-58.9	37.0-39.0	21.8	39.4-41.6	53.3-57.9
	10.0	92.7	9.6-10.2	21.8	10.2-10.9	93.9
5,000	10.0	93.2	11.8	21.75	10.6	94.2
	25.0	74.6-77.0	27.0	21.75	24.2	75.1-77.7
	50.0	50.9-56.5	44.4-55.5	21.75	39.9-49.8	50.3-55.7
10,000	50.0	53.2-59.8	52.8-67.6	21.9	39.2-50.2	53.6-59.5
	25.0	79.8-82.0	31.1-35.0	21.9	23.1-26.0	80.5-83.0
	10.0	92.9-93.2	13.1-14.8	21.9	9.7-11.0	93.3
15,000	10.0	92.9	16.5-18.2	21.5	10.0-11.1	94.6
	25.0	81.5-83.5	40.2-43.2	21.5	24.5-26.3	82.3-84.7
	50.0	56.6-63.7	62.2-79.9	21.5	37.9-48.7	56.4-63.5
20,000	50.0	64.5-71.9	57.7-82.9	21.8	28.7-41.2	58.4-65.0
	25.0	84.9-86.9	42.6-51.3	21.8	21.2-25.5	85.2-87.2
	10.0	93.2	20.5-22.7	21.8	10.2-11.3	94.6
22,500	10.0	94.1	19.9-21.4	21.9	8.9-9.6	94.7
20,000	10.0	94.05	20.3-22.4	22.0	10.1-11.1	94.7
	25.0	84.6-86.2	45.0-52.4	22.0	22.4-26.1	84.7-86.5
15,000	25.0	85.0-86.4	37.3-41.2	22.5	22.8-25.2	83.7-85.7
	50.0	59.0-65.3	71.5-77.8	22.2	43.7-47.5	56.5-63.4
	10.0	93.2	16.9-18.2	22.2	10.3-11.1	94.5
Ground	10.0	93.8	10.0	22.6	10.7	93.2
	25.0	74.3-75.5	22.9-24.1	22.6	24.5-25.8	73.7-75.2
	50.0	49.6-54.5	39.0-47.0	22.6	41.7-50.2	48.5-53.2
	58.0	46.2-49.9	42.7-54.0	22.6	45.6-57.7	44.8-49.4

RESULTS AND DISCUSSION

From the data gathered and analyzed, the respirable gases generated by the OBOGS can be measured by the ultrasonic oxygen sensor from ground level to better than 20,000 ft. These data (accurate to 1%) are output at a sample rate of 5 Hz (200 ms).

The ultrasonic oxygen sensor can measure O_2 flow rates up to 50 standard L/min. The flow rate accuracy is difficult to ascertain because of the flow rate fluctuations from the OBOGS. The flow rate readings, converted to standard L/min, indicate a lower value than the setting of the mass flowmeter; however, at high flow rates the mass flowmeter fluctuated around the flow setting.

The measurements of O_2 concentration and the flow rate followed the output of the OBOGS as registered by the Medical Gas Analyzer, generally within 1% and often within 0.5%.

The curve of O_2 concentration as a function of γ/M can be used to compute O_2 concentration as a linear function. From a computed γ/M, the O_2 concentration can be calculated.

If the design requirement for flow rate is dropped from the specifications, the ultrasonic oxygen sensor can be improved and the physical size of the chamber can be reduced.

APPENDIX

NATIONAL BUREAU OF STANDARDS

THERMODYNAMICS LABORATORY

THERMODYNAMIC DATA FOR NITROGEN AND ARGON

NITROGEN

ID	PRES MM HG	TEMP K	DENS MOL/L	CV J/(MOL*K)	CP J/(MOL*K)	CP/CV
1	760.	220.0	.05548	20.795	29.191	1.403752
2	760.	225.0	.05424	20.794	29.185	1.403565
3	760.	230.0	.05305	20.793	29.181	1.403391
4	760.	235.0	.05192	20.792	29.176	1.403227
5	760.	240.0	.05083	20.792	29.172	1.403074
6	760.	245.0	.04979	20.791	29.169	1.402930
7	760.	250.0	.04879	20.791	29.165	1.402793
8	760.	255.0	.04783	20.791	29.162	1.402662
9	760.	260.0	.04690	20.791	29.160	1.402538
10	760.	265.0	.04601	20.791	29.157	1.402418
11	760.	270.0	.04516	20.791	29.156	1.402302
12	760.	275.0	.04434	20.792	29.154	1.402189
13	760.	280.0	.04354	20.792	29.153	1.402078
14	760.	285.0	.04278	20.793	29.152	1.401969
15	760.	290.0	.04204	20.795	29.151	1.401861
16	760.	295.0	.04132	20.796	29.151	1.401753
17	760.	300.0	.04063	20.798	29.151	1.401644
18	760.	305.0	.03996	20.800	29.151	1.401534
19	760.	310.0	.03932	20.802	29.152	1.401422
20	760.	315.0	.03869	20.804	29.153	1.401308
21	760.	320.0	.03809	20.807	29.155	1.401191
22	760.	325.0	.03750	20.811	29.157	1.401070
23	760.	330.0	.03693	20.814	29.159	1.400945
24	760.	335.0	.03638	20.818	29.162	1.400815
25	760.	340.0	.03584	20.823	29.166	1.400681
26	760.	345.0	.03532	20.827	29.170	1.400541
27	760.	350.0	.03482	20.833	29.174	1.400394
28	760.	355.0	.03432	20.838	29.179	1.400242
29	760.	360.0	.03385	20.844	29.184	1.400083
30	760.	365.0	.03338	20.851	29.190	1.399916
31	760.	370.0	.03293	20.858	29.196	1.399742
32	760.	375.0	.03249	20.866	29.203	1.399561
33	760.	380.0	.03206	20.874	29.210	1.399371
34	760.	385.0	.03165	20.882	29.218	1.399173
35	760.	390.0	.03124	20.892	29.227	1.398966
36	760.	395.0	.03085	20.901	29.236	1.398750
37	760.	400.0	.03046	20.912	29.246	1.398526
38	760.	405.0	.03006	20.922	29.256	1.398292
39	760.	410.0	.02972	20.934	29.266	1.398049
40	760.	415.0	.02936	20.946	29.278	1.397796
41	760.	420.0	.02901	20.958	29.290	1.397535

ID	PRES MM HG	TEMP K	DENS MOL/L	CV J/(MOL*K)	CP J/(MOL*K)	CP/CV
42	630.	220.0	.04598	20.792	29.174	1.403129
43	630.	225.0	.04495	20.791	29.170	1.402974
44	630.	230.0	.04397	20.791	29.166	1.402830
45	630.	235.0	.04303	20.790	29.162	1.402694
46	630.	240.0	.04213	20.790	29.159	1.402567
47	630.	245.0	.04127	20.789	29.156	1.402446
48	630.	250.0	.04044	20.789	29.153	1.402332
49	630.	255.0	.03964	20.789	29.151	1.402223
50	630.	260.0	.03888	20.789	29.149	1.402118
51	630.	265.0	.03814	20.789	29.147	1.402017
52	630.	270.0	.03743	20.790	29.145	1.401918
53	630.	275.0	.03675	20.790	29.144	1.401822
54	630.	280.0	.03609	20.791	29.143	1.401726
55	630.	285.0	.03546	20.792	29.143	1.401632
56	630.	290.0	.03484	20.793	29.143	1.401537
57	630.	295.0	.03425	20.795	29.143	1.401442
58	630.	300.0	.03368	20.796	29.143	1.401345
59	630.	305.0	.03313	20.798	29.144	1.401247
60	630.	310.0	.03259	20.801	29.145	1.401146
61	630.	315.0	.03207	20.803	29.146	1.401042
62	630.	320.0	.03157	20.806	29.148	1.400935
63	630.	325.0	.03108	20.810	29.150	1.400823
64	630.	330.0	.03061	20.813	29.153	1.400707
65	630.	335.0	.03016	20.817	29.156	1.400586
66	630.	340.0	.02971	20.822	29.160	1.400460
67	630.	345.0	.02928	20.826	29.164	1.400327
68	630.	350.0	.02886	20.832	29.168	1.400189
69	630.	355.0	.02845	20.837	29.173	1.400043
70	630.	360.0	.02806	20.844	29.179	1.399891
71	630.	365.0	.02767	20.850	29.185	1.399730
72	630.	370.0	.02730	20.857	29.191	1.399563
73	630.	375.0	.02694	20.865	29.198	1.399387
74	630.	380.0	.02658	20.873	29.206	1.399203
75	630.	385.0	.02623	20.882	29.214	1.399010
76	630.	390.0	.02590	20.891	29.222	1.398808
77	630.	395.0	.02557	20.901	29.232	1.398597
78	630.	400.0	.02525	20.911	29.241	1.398378
79	630.	405.0	.02494	20.922	29.252	1.398148
80	630.	410.0	.02463	20.933	29.263	1.397910
81	630.	415.0	.02434	20.945	29.274	1.397662
82	630.	420.0	.02405	20.958	29.286	1.397404
83	630.	425.0	.02376	20.971	29.299	1.397136

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ARGON

ID	PRES MM HG	TEMP K	DENS MOL/L	CV J/(MOL*K)	CP J/(MOL*K)	CP/CV
1	760.	220.0	.05551	12.487	20.888	1.672768
2	760.	225.0	.05427	12.486	20.883	1.672462
3	760.	230.0	.05308	12.485	20.878	1.672177
4	760.	235.0	.05195	12.484	20.873	1.671911
5	760.	240.0	.05086	12.484	20.869	1.671663
6	760.	245.0	.04961	12.483	20.865	1.671429
7	760.	250.0	.04881	12.482	20.861	1.671211
8	760.	255.0	.04785	12.482	20.857	1.671006
9	760.	260.0	.04693	12.481	20.854	1.670813
10	760.	265.0	.04604	12.481	20.851	1.670631
11	760.	270.0	.04518	12.481	20.848	1.670460
12	760.	275.0	.04436	12.480	20.846	1.670298
13	760.	280.0	.04356	12.480	20.843	1.670146
14	760.	285.0	.04279	12.480	20.841	1.670002
15	760.	290.0	.04205	12.479	20.839	1.669866
16	760.	295.0	.04134	12.479	20.837	1.669737
17	760.	300.0	.04065	12.479	20.835	1.669614
18	760.	305.0	.03998	12.479	20.833	1.669498
19	760.	310.0	.03933	12.478	20.831	1.669388
20	760.	315.0	.03871	12.478	20.830	1.669284
21	760.	320.0	.03810	12.478	20.828	1.669184
22	760.	325.0	.03751	12.478	20.827	1.669090
23	760.	330.0	.03694	12.478	20.825	1.668999
24	760.	335.0	.03639	12.478	20.824	1.668914
25	760.	340.0	.03585	12.477	20.823	1.668832
26	760.	345.0	.03533	12.477	20.822	1.668754
27	760.	350.0	.03483	12.477	20.820	1.668679
28	760.	355.0	.03434	12.477	20.819	1.668608
29	760.	360.0	.03386	12.477	20.818	1.668540
30	760.	365.0	.03339	12.477	20.817	1.668475
31	760.	370.0	.03294	12.477	20.816	1.668413
32	760.	375.0	.03250	12.477	20.815	1.668353
33	760.	380.0	.03207	12.477	20.815	1.668296
34	760.	385.0	.03166	12.476	20.814	1.668241
35	760.	390.0	.03125	12.476	20.813	1.668189
36	760.	395.0	.03085	12.476	20.812	1.668139
37	760.	400.0	.03047	12.476	20.811	1.668091
38	760.	405.0	.03009	12.476	20.811	1.668044
39	760.	410.0	.02972	12.476	20.810	1.668000
40	760.	415.0	.02936	12.476	20.809	1.667957
41	760.	420.0	.02901	12.476	20.809	1.667916

ID	PRES MM HG	TEMP K	DENS MOL/L	CV J/(MOL*K)	CP J/(MOL*K)	CP/CV
42	630.	220.0	.04600	12.485	20.871	1.671720
43	630.	225.0	.04497	12.484	20.866	1.671467
44	630.	230.0	.04399	12.483	20.862	1.671232
45	630.	235.0	.04305	12.482	20.858	1.671011
46	630.	240.0	.04215	12.482	20.854	1.670805
47	630.	245.0	.04128	12.481	20.851	1.670613
48	630.	250.0	.04045	12.481	20.848	1.670432
49	630.	255.0	.03966	12.480	20.845	1.670262
50	630.	260.0	.03889	12.480	20.842	1.670102
51	630.	265.0	.03816	12.479	20.840	1.669952
52	630.	270.0	.03745	12.479	20.838	1.669810
53	630.	275.0	.03676	12.479	20.835	1.669676
54	630.	280.0	.03610	12.478	20.833	1.669550
55	630.	285.0	.03547	12.478	20.832	1.669431
56	630.	290.0	.03486	12.478	20.830	1.669318
57	630.	295.0	.03426	12.478	20.828	1.669211
58	630.	300.0	.03369	12.478	20.826	1.669110
59	630.	305.0	.03314	12.477	20.825	1.669014
60	630.	310.0	.03260	12.477	20.824	1.668922
61	630.	315.0	.03208	12.477	20.822	1.668836
62	630.	320.0	.03158	12.477	20.821	1.668753
63	630.	325.0	.03109	12.477	20.820	1.668675
64	630.	330.0	.03062	12.477	20.819	1.668600
65	630.	335.0	.03016	12.477	20.817	1.668529
66	630.	340.0	.02972	12.476	20.816	1.668461
67	630.	345.0	.02929	12.476	20.815	1.668397
68	630.	350.0	.02887	12.476	20.814	1.668335
69	630.	355.0	.02846	12.476	20.814	1.668276
70	630.	360.0	.02807	12.476	20.813	1.668220
71	630.	365.0	.02768	12.476	20.812	1.668166
72	630.	370.0	.02731	12.476	20.811	1.668114
73	630.	375.0	.02694	12.476	20.810	1.668065
74	630.	380.0	.02659	12.476	20.810	1.668017
75	630.	385.0	.02624	12.476	20.809	1.667972
76	630.	390.0	.02590	12.476	20.808	1.667929
77	630.	395.0	.02558	12.475	20.808	1.667887
78	630.	400.0	.02526	12.475	20.807	1.667847
79	630.	405.0	.02494	12.475	20.806	1.667809
80	630.	410.0	.02464	12.475	20.806	1.667772
81	630.	415.0	.02434	12.475	20.805	1.667736
82	630.	420.0	.02405	12.475	20.805	1.667702
83	630.	425.0	.02377	12.475	20.804	1.667670

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